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The Development and Use of Thin Film Thermocouples for Contact Temperature Measurement©

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A procedure was developed for producing thin film thermocouples (TFTC) on the contact surface of sliding mechanical components. The thermocouple devices were made from thin films of vapor-deposited copper and nickel. The measuring junctions of the thermocouples were approximately 2 μm thick and between 80 μm and 300 μm across. The TFTC devices were found to have extremely rapid (< 1 μs) response to a sudden temperature change and did not significantly disturb the heat flow from the sliding contact. It was found necessary to sandwich the TFTC between thin films of a hard, non-conducting ceramic (Al_2O_3 in the current work) to insulate the thermocouple electrically from the substrate and protect it during sliding.

Thin film thermocouple devices were applied to the measurement of sliding surface temperatures in two cases, oscillatory dry sliding of a polymer pin on a flat surface, and uni-directional dry sliding of a ring over a flat pin surface. Results from the tests verified theoretical predictions.

INTRODUCTION AND BACKGROUND

The transformation of frictional energy to heat, called frictional heating, is responsible for increases in the temperatures of the sliding bodies, especially in the contact region. Surface and near-surface temperatures in the contacting bodies can become high enough to cause changes in the structure and properties of the sliding materials, oxidation of the surfaces, and possibly even melting of the contacting solids. For this reason it is important to be able to determine the surface temperatures of sliding contacts.

Techniques ranging from metallographic to optical to thermocouples have been used with varying degrees of success to measure the temperatures resulting from frictional heating (*1*). The most frequently used surface temperature sensor is the thermocouple, which is based on the findings of Seebeck in 1821. He demonstrated that a specific thermal electromotive force (EMF) potential exists as a property intrinsic to the composition of a wire, the ends of which are kept at two different temperatures. The simplest measuring circuit for thermometry would involve wires of two dissimilar metals connected together so as to give rise to a total relative Seebeck potential. This EMF is a function of the composition of each wire and the temperatures at each of the two junctions. This circuit can be well characterized such that, if one junction is held at a known reference temperature, the temperature of the other measuring junction can be inferred by comparison of the measured total EMF with an empirically derived calibration table (*2*).

The most common way to use a thermocouple to measure contact temperature is to embed the measuring junction within the stationary component of a frictional pair. Embedded thermocouples have been found to give a good indication of the transient changes in frictional heat generation which accompany contact area changes (*3*)–(*5*). They cannot, however, give a true indication of surface temperature peaks. Subsurface thermocouples have a limited ability to respond to flash temperatures, owing to their mass and their distance from the points of intimate contact where heat is being generated. A thermocouple can be made part of the sliding surface by placing it in a hole which extends to the surface, and then grinding the thermocouple even with the surface. Even in that case, the finite mass of the thermocouple junction prevents it from responding to the very localized, short duration flash temperatures (*5*).

In an attempt to get a better measure of actual surface temperatures, several other types of thermocouples have been used, such as contact and dynamic varieties. Contact thermocouples consist of two separate insulated wires embedded in one of the sliding components, which are joined together by deformation and frictional heating in the contact zone. They have been used in applications such as grinding (*6*), but concerns about their accuracy persist, owing to variable junction size and transient response. Dynamic thermocouples use the contacting bodies themselves, or portions of the bodies, as the thermocouple elements, and use the contact area as the measuring junction (*7*). They

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have also been used to make surface temperatures for certain combinations of sliding materials, but questions remain about the accuracy and meaning of the thermal EMF produced by the dynamic thermocouple.

In an attempt to avoid the difficulties encountered with other types of thermocouples in surface temperature measurement, we employed microelectronic fabrication techniques to produce thin film thermocouples. Thin film thermocouples (TFTCs) have been under development for a number of years, but have not previously, to the authors' knowledge, been used in measuring contact temperatures. Some of the earlier work on TFTC sensors described the properties of evaporated films of Ni-Fe, Cu-Fe, Cu-Ni, Cu-constantan, Fe-constantan and chromel-alumel thermocouple pairs (*8*). Although the thin film thermocouples did not give the same values of the relative Seebeck coefficient as the usual welded wire thermocouples, the output was consistent for film thicknesses greater than 250 nm and the results were quite reproducible (*8*). With the desire to measure temperatures in microelectronic devices in recent years, there has been an upsurge of interest in TFTC sensors and their response. The response times of thin film thermocouples have been determined to be in the microsecond range (*9*). They have been used in applications ranging from microelectronic device processing (*10*) to measuring the cylinder wall temperatures in internal combustion engines (*9*).

DEVELOPMENT OF A THIN FILM THERMOCOUPLE (TFTC) DEVICE

Requirements for TFTC Devices

Because of the peculiar environment encountered in sliding situations, the thin film thermocouple (TFTC) devices developed for contact surface temperature measurement in this work had to satisfy the following requirements:

1. Flash temperatures occur only at localized real contact areas and have very short durations. The TFTC device must have small measuring junction dimensions and a small thermal mass in order to achieve rapid thermal response and local area thermal sensitivities.
2. The TFTC device must have good wear resistance and reasonable durability during frictional sliding tests.
3. Since the TFTC device constitutes a electric circuit, it has to be electrically insulated from any conductive media.

To meet these requirements, the TFTC devices developed in this work were designed to have miniature measuring junctions, sandwiched by wear-resistant, electrically insulating protective layers.

Fabrication of the TFTC

The fabrication techniques reported here, although not optimally controlled, constitute well-established thin film practices. They have yielded TFTC devices that are reasonably durable and responsive, and demonstrate near-bulk relative thermoelectric power and linearity.

The TFTC device structure shown in Fig. 1 was that of pure metals, Ni and Cu, sandwiched between dielectric Al_2O_3.

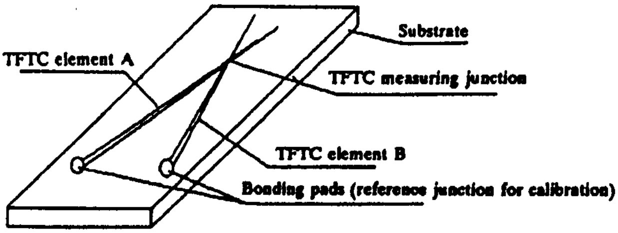


Fig. 1(a)—Schematic diagram of thin film thermocouple.

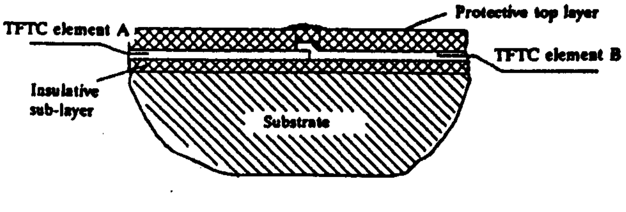


Fig. 1(b)—Schematic cross-section of thin film thermocouple.

The metal and dielectric films were grown by physical vapor deposition in a water-cooled stainless steel bell jar. A liquid nitrogen-filled Meissner trap was utilized above a 15 cm diameter diffusion pump. An ultimate vacuum lower than 3×10^{-6} Torr was readily achieved. The evaporation source-to-substrate distance was 22 cm. The substrate was radiantly heated to about 300°C by a nichrome wire mesh located 1 cm from the substrate backside. A type E thermocouple monitored the process temperature near the substrate back surface. A crystal monitor system was used to monitor deposition thickness and rate, with the quartz crystal mounted near the substrate. Monitor output was cross-calibrated with substrate film thickness step profiles measured with a stylus profilometer. The evaporation metals used were more than 99.9 percent pure. The Al_2O_3 was more than 97 percent pure. Two substrate types were used, commercial glass microscope slides and stainless steel slides, polished to 0.1 μm rms surface roughness, using alumina powers down to 0.3 μm size.

Each substrate was washed in water detergent, then ultrasonically degreased in acetone and subsequently buffed and wiped with an ethanol-soaked low particulate fabric. The substrates were precoated with Al_2O_3 evaporated from a e-gun source through a reactive oxygen backfill of 1×10^{-4} Torr. This layer served to improve metal adhesion to the glass substrate (0.15 μm thick Al_2O_3), or to electrically isolate the metal layers from the metal substrate (>1000 Megaohms with 5 μm thick Al_2O_3). Delineation of the metal runs was produced by a slit mask held in proximity to the substrate. The mask was fabricated by the electrical discharge machining of a thin stainless steel sheet (300 μm line width) or by aligning 2 razor blade edges fixed on the substrate (80 μm line width). With the slit mask in place, Ni was deposited from an e-gun source at a rate of about 2.5 nm/s, at a background pressure of 2×10^{-5} Torr. After the desired film thickness, generally 1 μm or less, had built up, the substrate was removed from the vacuum, the slit mask was re-aligned to delineate the second metal of the couple, and the substrate was then reloaded into the vacuum chamber. Cu was deposited at a rate of about 3.0 nm/s, at a background pressure of 2×10^{-5} Torr, from an alumina coated tungsten resistor boat. The copper layer was generally the same thickness as the Ni layer (up to 1 μm). A protective layer of 2 μm Al_2O_3 was deposited over the completed TFTC in a manner similar to the precoat, except that a shadow mask was used to prevent bond pad coverage. Extension wires were connected to the finished device using rosin core tin solder. The adhesion strength of the thin film structures was sufficient to withstand standard tape pull tests.

Calibration of the TFTC Devices

The thin film thermocouples were calibrated individually because earlier investigations of TFTCs had indicated that their relative Seebeck coefficients may not be equal to those of the bulk materials (*8*). Ambient room temperature was chosen as the reference temperature. Equilibrium ice-water and boiling water were used as two fixed points of calibration. A comparison method, using a reference thermometer, was employed for calibrating at other temperature points. Each of the thin-film metal runs was extended with conduction wires of respectively identical metals so as to obtain accurate calibration with respect to a room temperature reference junction remote from the measuring junction. During the calibration, the major temperature gradient was concentrated near the measuring junction. The basic thermocouple circuit used for this work is given in Fig. 2.

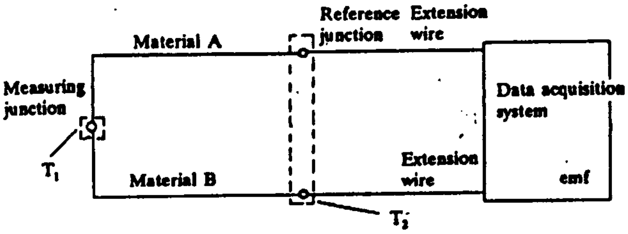


Fig. 2—Elementary circuit for monitoring TFTC. Junction 2 is held at a constant, known reference temperature—in this case, room temperature.

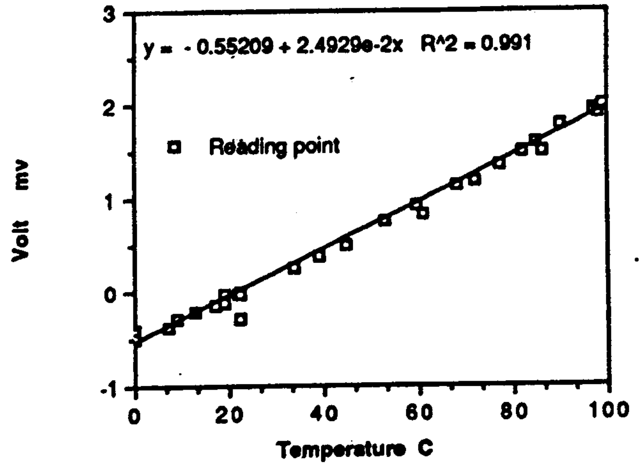
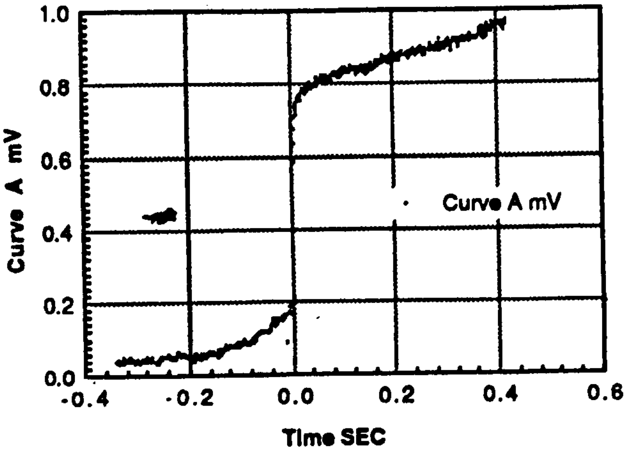


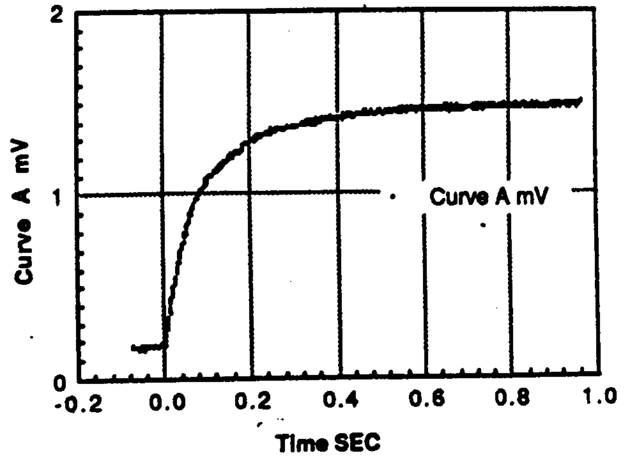
Fig. 3—Calibration results for a typical Cu-Ni thin film thermocouple. Reference temperature is 21°C.

Figure 3 shows a typical calibration result for a Cu-Ni TFTC device, using hot water up to the boiling point. The calibrations indicated that most of TFTC devices made in this work had similar relative thermal electric power, and these were approximately the same as what had been reported for wire thermocouples of the same materials (*11*). By rapidly immersing the TFTC measuring junction into hot water, a thermal response time of less than 3 ms was measured. The measured thermal response time probably had not come close to the lowest limit since the immersing speed of the measuring junction had matched response speed, and had, therefore, limited the thermal response time. Figure 4 shows a comparison of thermal responses from TFTC and wire thermocouples. Both thermocouples had been made from copper and nickel materials and both had been immersed into hot water at the same speed. It is apparent that a thin film thermocouple will respond faster than a wire thermocouple, primarily because its junction mass is much less. For example, a small wire thermocouple bead might be approximated by a sphere of 500 μm di-



(a)

Fig. 4(a)—Response of Cu-Ni thin film thermocouple when rapidly immersed in hot water.



(b)

Fig. 4(b)—Response of Cu-Ni wire thermocouple when rapidly immersed in hot water.

ameter. That junction would have about 400 times the volume of the largest TFTC junctions used in this work, approximately 300 µm × 300 µm × 2 µm. The difference would be considerably greater with smaller TFTC devices. It might be noted from Fig. 4(a) that the TFTC device rapidly rose to a temperature between that of the hot water in which it was immersed and that of the glass substrate on which it was mounted. After the rapid initial increase, as the substrate temperature gradually rose, the TFTC indicated a gradually increasing temperature.

ANALYSIS OF THERMAL RESPONSE AND HEAT FLOW DISTURBANCE OF THE TFTC

As was seen above, one of the main advantages of using a thin film thermocouple as a surface temperature measurement sensor is that the TFTC has an extremely low measuring junction mass. This should lead to a much more rapid signal response than normal wire thermocouples, and should also result in a very modest disturbance of heat transfer in the contact region. In order to quantify these two advantages, analytical work was carried out to study the thermal behavior of TFTC devices in a sliding contact situation.

Analysis of TFTC Thermal Response

To get a conservative estimate of the response of a thin film thermocouple, a TFTC junction was treated as a thermal system and the heat flow into that system was analyzed. The thermal response of the junction was determined for the case of a sudden input of heat. It was assumed that during the short time required for the thermocouple to heat, conduction was the dominant mode of heat transfer, so convection and radiation were neglected. Heat was assumed to be input over a square contact area, and methods described in Carslaw and Jaeger (*12*) were used in the study. From the analysis, it was found that a typical copper-nickel thin film thermocouple would exhibit a 95 percent response to a step temperature change within 1 µs. This estimate shows that the transient output shown in Fig. 4(a) was dominated by the time required to submerge the thermocouple junction in hot water, and not by the thermocouple response.

Numerical Simulation of Heat Flow Disturbance of TFTC

The heat flow disturbance caused by the presence of the thin film thermocouple was studied with the aid of a finite element package, Thermap, which had been developed specifically for studying surface temperature problems in sliding systems (*13*). The physical model used in this problem was a two-dimensional half-space covered with a 10 µm thick protective coating as shown in Fig. 5. A 5 µm thick by 0.1 mm wide TFTC measuring junction was assumed to be located beneath the contact zone and subjected to a 0.1 mm wide uniform band heat source. It should be noted that the numerical results from this model will provide a conservative upper limit estimate of the heat flow disturbance that occurs in practical applications. For the TFTC devices made in this work, the measuring junctions were 2 µm thick or

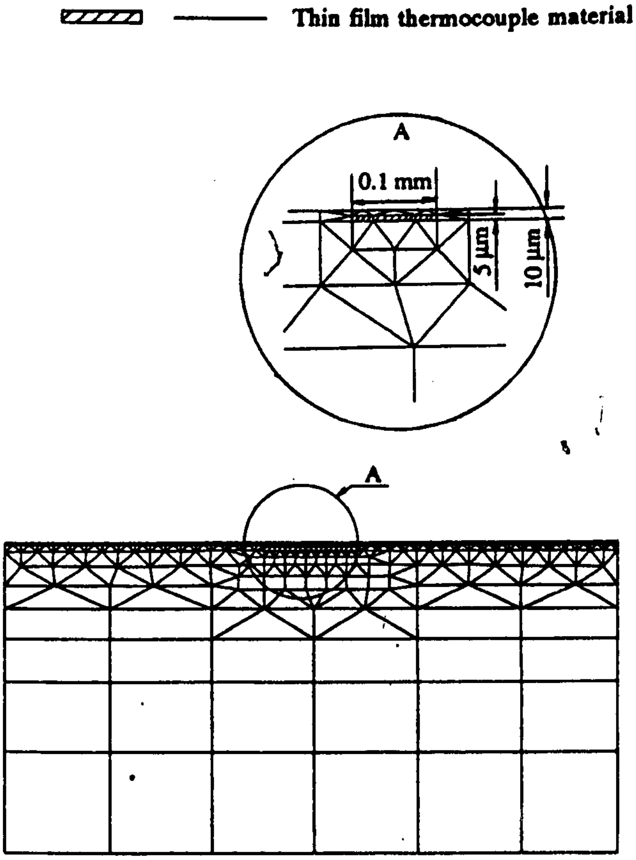


Fig. 5—Finite element model used to analyze heat flow disturbance of TFTC. (10 µm thick protective coating, 5 µm thick × 0.1 mm wide thermocouple)

applications. For the TFTC devices made in this work, the measuring junctions were 2 µm thick or less and the pro- less and the protective layer above the TFTC junction was also less than 2 µm thick.

The numerical simulation for heat flow disturbance of the TFTC was carried out for two situations, change of moving velocity, and change of the ratio of thermal conductivity of the TFTC to that of thin film layer surrounding the thermocouple.

Figure 6 shows the variation of heat flow disturbance of TFTC for different sliding velocities. It can be seen from the figure that there is a very small surface temperature difference between layered bodies with and without a TFTC under the contact zone. The difference decreases with an increase of moving velocity and the largest temperature difference was found to be only 3 °C. The heat input to the contact area is balanced by both heat conduction and convection, and the presence of a small TFTC measuring junction beneath the contact area only affects heat transfer in the conduction mode. Therefore, an increase of velocity will increase heat transfer by convection and reduce the heat flow disturbance caused by the thermocouple.

Figure 7 represents the computed maximum surface temperature rise for different ratios of thermal conductivity of the TFTC to that of the thin film layer. It can be seen that the heat flow disturbance of the TFTC is very small when

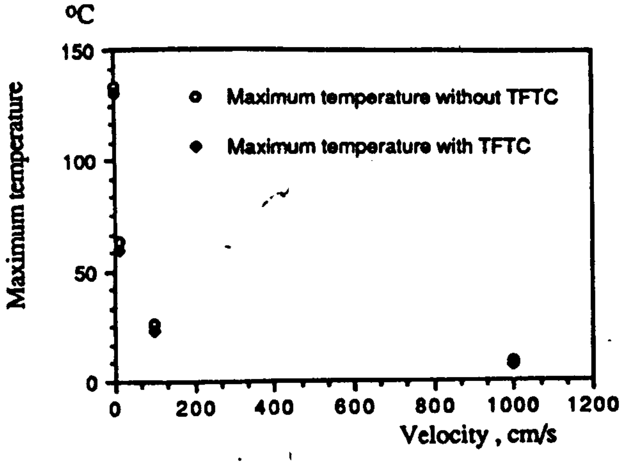


Fig. 6—Result of numerical analysis for heat flow disturbance of TFTC at various moving velocities.

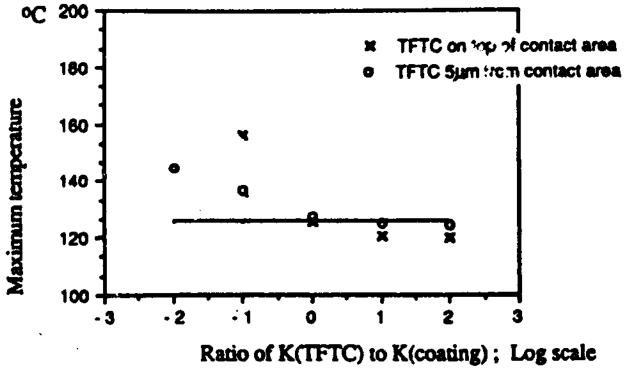


Fig. 7—Result of numerical analysis for heat flow disturbance of TFTC at various ratios of thermal conductivity of TFTC to thermal conductivity of coating.

the thermal conductivity of TFTC is higher than that of the thin film layer. When a TFTC is on the contacting surface, the surface temperature difference is less than 6 °C, even if the ratio of thermal conductivity of TFTC to that of the thin film layer is as high as 100. When a TFTC measuring junction is 5 μm away from the contact surface, the surface temperature difference is less than 3 °C when the ratio of thermal conductivity of TFTC to that of the thin film layer is 100 or less. This indicates that the effect of the heat flow disturbance of the TFTC in a sliding contact situation is very small if the thermal conductivity of the thermocouple materials is close to or higher than that of the thin film layer. Usually one can simply neglect the effect of the heat flow disturbance of a TFTC, since the thermal conductivities of common engineering thermocouple materials are close to or higher than those of typical thin film layer materials.

CONTACT SURFACE TEMPERATURE MEASUREMENT TESTS USING THE TFTC

Pin-on-Disk Oscillatory Dry Sliding Test

Sliding surface temperatures were measured using the TFTC technique for polymer pins (PTFE) against Al_2O_3-coated glass and stainless steel flats in dry oscillatory sliding. A pin-on-flat oscillatory wear tester, described in detail elsewhere (*14*), was used in this surface temperature measuring test. The tester allowed oscillatory contact between a stationary polymer pin and an oscillating flat at an oscillation amplitude of either 0.5 mm or 4 mm. Oscillation frequencies ranged from 0 to 40 Hz for 0.5 mm amplitude, and 0 to 10 Hz for 4 mm amplitude. The pin had a cross-section of 2 mm × 4 mm, with the 4 mm dimension in the sliding direction. An Ni-Cu TFTC was fabricated on the surface of a Al_2O_3 coated glass or stainless steel flat substrate. The measuring junction of the TFTC was located at the center of contact area when the test system was at rest. During the tests, a normal force of 52.4 N was applied to the top of the polymer pin and the friction force was measured by a piezoelectric force transducer.

For the PTFE polymer pin against Al_2O_3-coated glass or stainless steel substrates, the measured friction coefficient was found to range from 0.09 to 0.13. The thermocouple signals due to the local temperature rise at the TFTC measuring junction were monitored continuously by a computerized oscilloscope system with a data acquisition rate of 20 μs/point (50 kHz). The measured temperature data were stored on magnetic disks for later analysis. Figure 8 shows

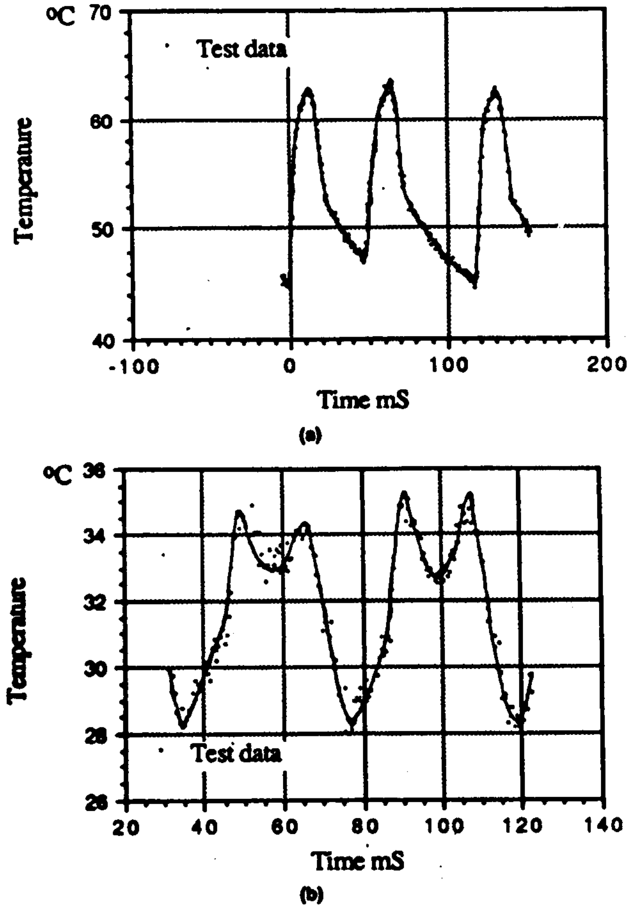


Fig. 8—Measured surface temperature rise in oscillatory sliding test of PTFE pin on Al_2O_3-coated glass flat. Normal load = 52.4N.
(a) amplitude = 4.0 mm, frequency = 9 Hz, measured friction force = 6.67 N
(b) amplitude = 0.5 mm, frequency = 23.8 Hz, measured friction force = 7.04 N

the typical surface temperature variation measured at the TFTC junction during the tests. The temperature measurements in this case confirm the theoretical prediction (*13*)–(*15*) that the transient surface temperature variation has two peaks during each period of oscillation, with the maximum temperature rise occurring at the time of maximum friction heat input, i.e., the maximum sliding speed. The amplitude of motion had a substantial influence on the shape of the transient temperature variation. Sliding velocity had a major influence on surface temperature, as was expected, since that parameter controlled the rate of frictional heat generation. It was also found that the thermal properties of the flat substrate materials had a significant effect on the maximum surface temperature rise. For a glass substrate, the measured maximum temperature rise above the ambient room temperature reached 70 °C, but for stainless steel substrates the measured maximum temperature rise under similar sliding conditions was only in the range of 8 °C. This is due to the fact that nearly all of the frictional heat enters the flat in this case, and the thermal conductivity of the flat determines the bulk temperature of that component.

Figure 9 shows one of the thin film thermocouples after being rubbed by a PTFE pin in a typical sliding test. It is evident that a thin transfer film of PTFE has covered the thermocouple junction. It is known that transfer films form whenever PTFE slides over a metallic substrate, with the rate of transfer film formation being influenced by surface temperature (*16*). The measured temperature did not vary significantly as the transfer film built up during the sliding test, so the very thin (<1 μm thick) transfer film seemed to have little influence on the magnitude of temperature measured by the TFTC.

Pin-on-Ring Unidirectional Dry Sliding Test

In this case, the sliding surface temperature was measured during dry sliding of a carbon-graphite ring against an Al_2O_3-coated glass flat. The test was performed on a wear test machine which had previously been used for wear and face seal investigations and was described in detail elsewhere (*17*). An Ni-Cu TFTC was located on the contacting surface of the coated glass substrate, which was mounted on a stationary specimen holder. The carbon-graphite ring, with a diameter of 50 mm and a face width of 2.5 mm was rotated against the surface of glass substrate, with the TFTC measuring junction at the center of the contact interface. The sliding speed was 1.57 m/s (600 rpm) and a normal force ranging from 30 to 60 N was applied to the rotating carbon-graphite ring. The friction force was measured by a strain gauge transducer.

Figure 10 shows an example of the surface temperature variation measured by the TFTC device at the measuring junction. The period from the beginning of the temperature rise above bulk temperature to the maximum peak temperature indicates the start and the end of an asperity contact during sliding. According to the test records, contact between the TFTC measuring junction and asperities occurred once per revolution and each contact duration was about 2 ms. Based on the measured temperature profile in Fig. 10, a contact length (sliding direction) of 3 mm was obtained. The measured maximum surface temperature rise for this case was 100.2°C above the ambient room temperature. Examination of the wear surface of the coated TFTC devices after the tests showed that the TFTC devices had relatively good wear resistance. Care had to be taken in handling the TFTC devices with glass substrates since glass is very brittle and cracks were easily formed at the surface. Care was also required to prevent the connecting wires from separating from the TFTC device's bond pads.

DISCUSSION OF RESULTS

Some interesting observations were made during the surface temperature measurement tests. For a sliding test such as the pin-on-ring configuration used in this study, the conventional model for surface temperature analysis usually assumes that the pin element is stationary relative to the heat source and the counterpart ring is moving. However, the measured surface temperature transient on the pin surface, shown in Fig. 10, had the same character as the surface temperature profile of a moving body. Thus, the frictional

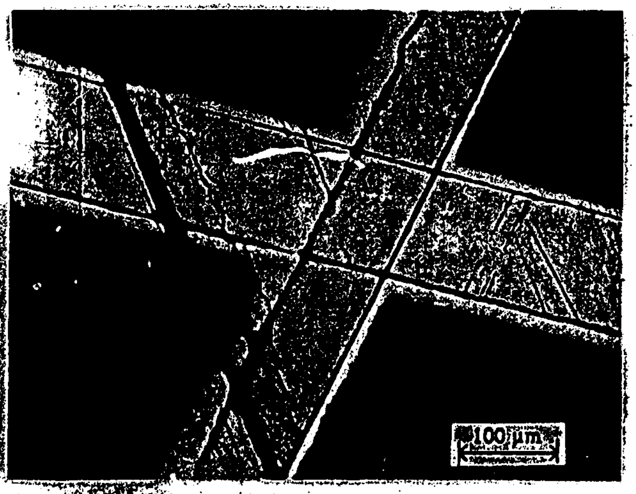


Fig. 9—Sliding surface of TFTC after oscillatory test of PTFE pin over alumina-coated glass flat.

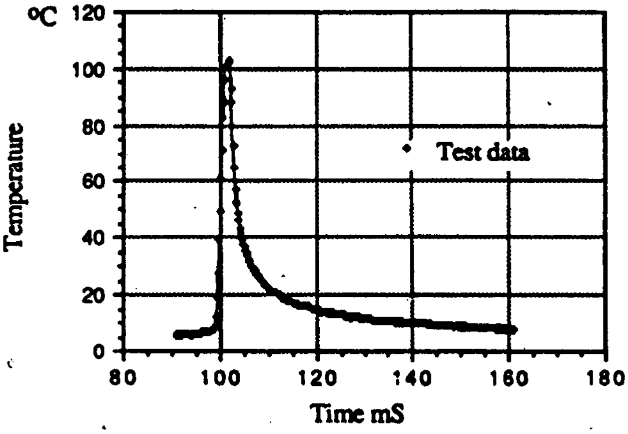


Fig. 10—Output of TFTC during dry sliding test of carbon-graphite ring against alumina-coated glass flat.

heating problem in this case should be treated as one in which an asperity on the ring surface slides past an asperity on the pin surface. Using this model, the theoretical prediction of the maximum surface temperature was found to be quite close to the measured maximum temperature rise.

For oscillatory sliding contact, the experimental results indicated that the contact surface temperatures varied in a harmonic manner, consistent with the oscillating motion. It was found that the oscillating frequency for a given amplitude greatly affected the maximum surface temperature rise, see Fig. 11. It was also found that when the product of oscillating frequency and amplitude was fixed, i.e., the maximum sliding velocity was fixed, the mean surface temperature decreased with an increase of oscillation amplitude. Figure 12 shows the transient contact surface temperature variation at a fixed amplitude, from both the beginning and the end of a sliding test. Although theoretical predictions had predicted that the quasi-steady state would be reached after 10–15 cycles (*15*), the current test results showed that the quasi-steady state was not reached until 25 cycles. Examining the temperature variation in Fig. 12, the authors found that the entire surface temperature rise could be divided into two contributions, a bulk temperature rise, plus a transient temperature variation. For transient temperature variations, the quasi-steady state could be reached in only a few cycles, possibly in only one cycle if the mechanical inertial effects of the oscillating sliding tester were excluded. This experimental result was in good agreement with theoretical predictions about how long it would take for the quasi-steady state to be reached for the transient flash temperature in either unidirectional or oscillating sliding systems (*13*). Conversely, the bulk temperature would increase with time, independent of transient temperature variations, until it reached the steady state. It was found that amplitudes of both the surface temperature variation and bulk temperature rises depended on the amplitude and frequency of oscillation.

It should be noted that the temperature rise measured by the TFTC technique is actually the temperature difference between the local temperature at the TFTC measuring junction and the temperature of the reference junction. Care must be taken to keep the temperature at the reference junction relatively unaffected by external heat sources during both calibration and experiments.

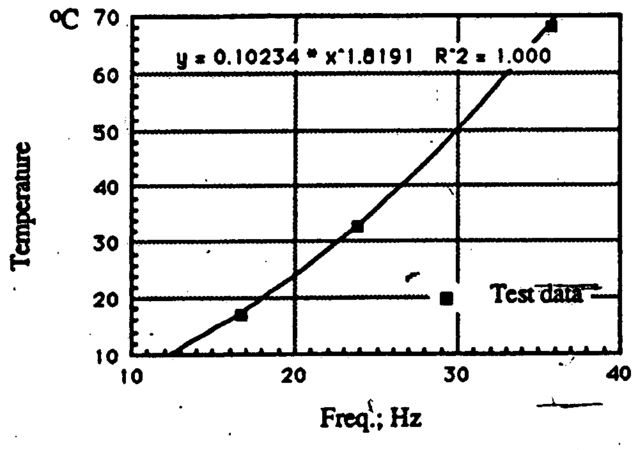


Fig. 11—Measured surface temperature in oscillatory test of PTFE pin on glass flat as function of oscillation frequency. Oscillation amplitude = 0.5 mm.

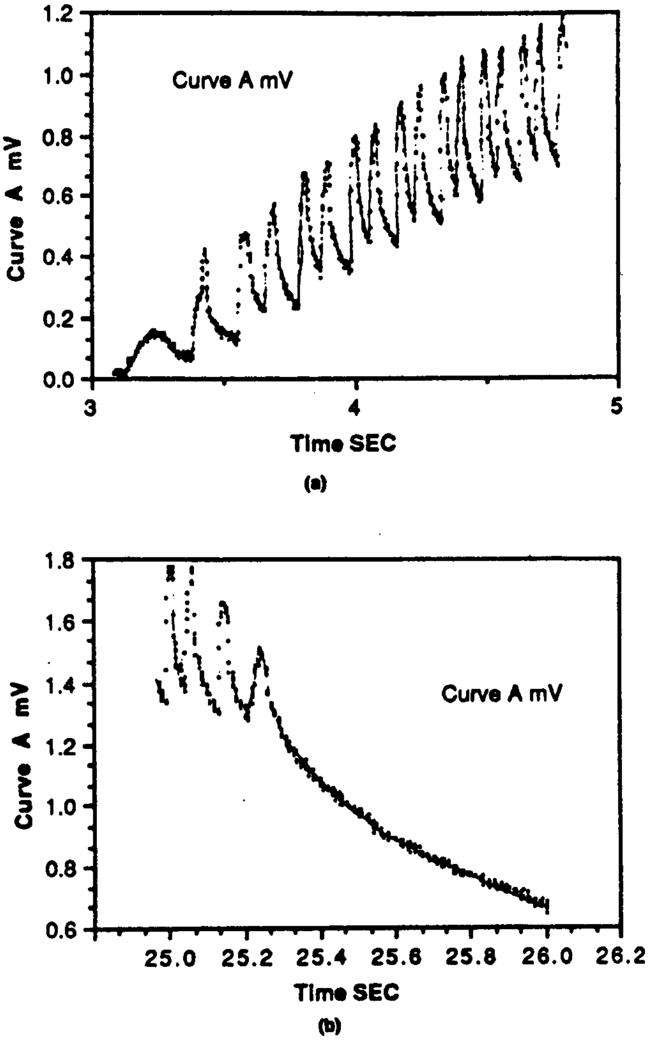


Fig. 12—TFTC output in oscillatory test of PTFE pin on glass flat. Amplitude = 4.0 mm, normal load = 52.4 N.
(a) beginning of test
(b) end of test

There also exists a difference between the real surface temperature on the contact interface and the measured temperature at the TFTC measuring junction, which may be several micrometers beneath the contact surface. This temperature difference is very small under low speed sliding conditions, and it can be entirely neglected if the thermocouple is stationary relative to the contact area in which frictional heat is being generated. If the contact area is moving at a high velocity relative to the TFTC, however, there could be a significant difference between the surface temperature and the temperature at the measuring junction just beneath the surface. The difference between surface and subsurface temperatures can be predicted by analytical techniques. For the experimental cases discussed above, the difference between surface and measured temperatures was found to be zero for the oscillatory polymer sliding test and about 10–12 percent for the high speed unidirectional sliding test. Details of the analytical technique will be published later.

CONCLUSIONS

A procedure for fabricating Ni-Cu thin film thermocouples has been described. The measuring junctions of the vapor-deposited thermocouples were about 2 μm thick and between 80 μm and 300 μm across. The current investigations show that Ni-Cu TFTCs exhibit a relative thermoelectric power similar to the bulk materials, but the TFTC devices should be calibrated individually because of slight variations in thermoelectric power among TFTC devices.

The theoretical and numerical analyses in this work show that the TFTC device exhibits a fast thermal response time (below one micro-second) and very small heat flow disturbance when used in sliding contact situations.

Two types of sliding tests were performed using the TFTC surface temperature measuring technique. Results from the tests verified the theoretical predictions and gave physical evidence which was previously unavailable. In all cases, the TFTC technique developed in this research has proved to be a quite promising method for the measurement of surface temperatures in both unidirectional and oscillatory sliding contacts.

ACKNOWLEDGMENTS

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DISCUSSION

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Many researchers have pursued evaporated thermocouple or thermistor techniques for surface temperature measurements. Early work with thermocouples was conducted by Cheng and Orcutt (*D1*). Work with thermistors was performed by Kannel and Dow (*D2*). To be valuable, of course, the research should be done with metallic substrate rather than glass. The large difference in conditions between glass and steel make it unrealistic to attempt to extrapolate from temperatures on glass surfaces to temperatures on steel surfaces.

The problem with measurements on steel surfaces is, of course, the requirement of an insulating surface layer. This insulating layer alters the surface temperature. The effect of the layer can be minimized by using very thin layers (less than 1 μm). The authors talk of using 5 μm layers which may be required for thermocouples. Did the authors consider using simple thermistors?

Why did the authors coat Al_2O_3 layers in thin glass substrate? There are many ways to prepare a glass surface for vapor deposition without altering the heat conduction of the surface.

With regard to calibration of the thermocouple, the discussors' experience has been that accurate calibration requires a highly controlled atmosphere. The discussors also tried dipping the thermocouples in hot water and found little agreement with published values of sensitivity. Could the author comment on the accuracy of the calibration technique?

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AUTHORS' CLOSURE

The authors wish to thank the discussors for their pertinent comments. Both thin film thermocouples and thin layer thermistors have their own merits for measuring contact temperature rise. Vapor-deposited thermistors have proven useful in measuring surface temperatures in elastohydrodynamically lubricated contacts, but have not, to the authors' knowledge, been used in unlubricated sliding, which was the topic of tne current study. Thermistors have several disadvantages relative to thermocouples for contact temperature measurement, namely, the larger size of thermistors and the dependence of their output on contact pressure and on temperature gradients along the extension lead wires as well as on contact temperature.

Alumina layers, sometimes as thin as 10 nm, were found to improve the adhesion of the metallic thermocouple elements to glass substrates, although the alumina bond layers were not absolutely necessary. Analysis showed that the thin alumina layers had essentially no influence on heat conduction into the glass substrate. When used on metallic substrates, the Al_2O_3 layers had to be thicker to completely insulate the thermocouple from substrate.

Liquid bath calibration techniques were found to be quite accurate in the 0° to 100°C range, as long as the bulk temperature of the substrate was allowed to reach steady state. Less than 1°C difference was found between TFTC output value and the real temperature it represented. Owing to the temperature limitations of liquid bath calibration methods, the authors have been using laser-based heat input techniques to calibrate thin film thermocouples at higher temperatures.